VENTILATION SYSTEM DESIGN AND LARGE SCALE FIRE TESTS

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ABSTRACT

The design, construction and operation of the tunnels of M-30, the major ring road in the city of Madrid (Spain), represent a very interesting project in which a wide variety of situations – geometrical, topographical, etc. - had to be covered, in variable conditions of traffic. For that reasons, the M-30 project is a remarkable technical challenge, which, after its completion, turned into an international reference.

From the 'design for safety' perspective, a holistic approach has been used to deal with new technologies, integration of systems and development of procedures to reach the maximum level. However, one of the primary goals has been to achieve reasonable homogeneity characteristics which can permit operate a network of tunnels as one only infrastructure.

In the case of the ventilation system the mentioned goals have implied innovative solutions and coordination efforts of great interest. Consequently, this paper describes the principal ideas underlying the conceptual solution developed focusing on the principal peculiarities of the project.

Keywords: ventilation design, city tunnels, environmental management

1. INTRODUCTION

Traditionally, the construction of long size tunnels has been associated with major interurban roads or railway lines. However, in the urban scope, large road tunnels have seldom been constructed due to the inherent characteristics of the urban traffic.

In the last decades, an improvement of the environmental conditions, as well as the need of recovering urban spaces for social purposes, joined the growth of major cities. In the city of Madrid this trend has taken the form of the works of coverage of an important part of the M-30, major ring road of the city of Madrid, which had been surrounded by the urban buildings due to the growth of the city.

The project for the redesigning of the M30 (Madrid M30, 2007), with more than 71 different construction works all along the ring road and peripheral routes, has been completed during the cycle 2003-2007 and among these actuations, several tunnels of moderated length have been constructed (O'Donnel, 1440 m; Ventisquero de la Condesa, 1500 m; Costa Rica, 630 m; Sor Angela de la Cruz, 1600 m; Embajadores-M40, 1800 m).

However, the most challenging project included an underground network of different tunnels, with a total length of more than 40 km of twin tubes tunnels. One of the most interesting aspects is that due to administrative and organizational reasons the whole project was divided into smaller sub-projects. Consequently, each one of them was awarded to different construction companies or joint ventures of them (figure 1).

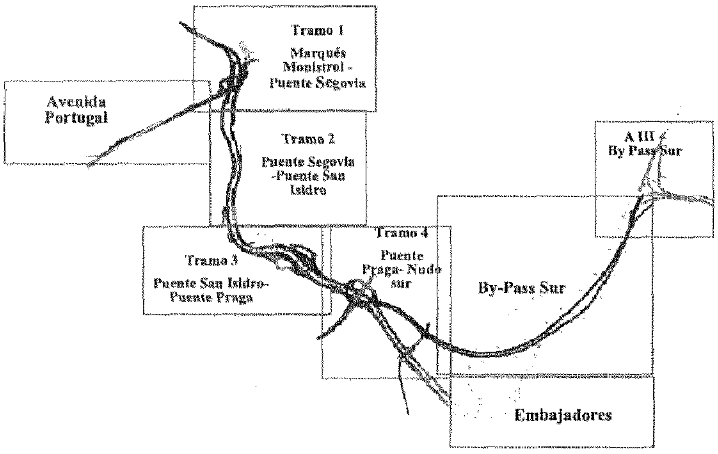


Figure 1: General layout of the project and administrative division.

By one side, this disaggregation permitted a quick execution with enormous human and technical resources; from the other, coordination to get the necessary homogeneity between all the works was of the utmost importance.

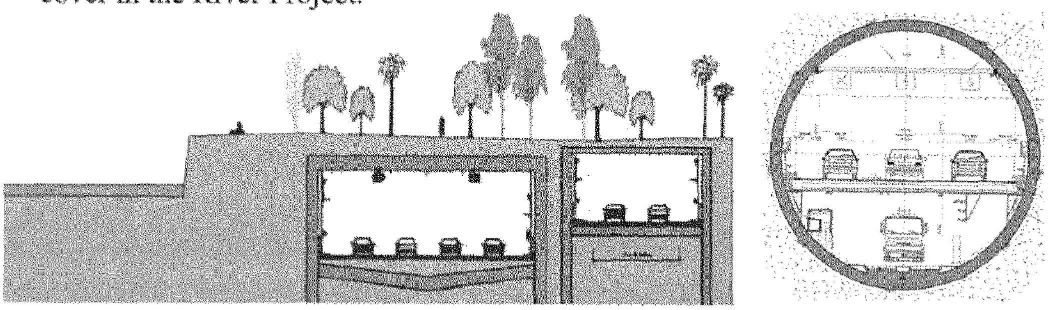
Looking to the past, it must be said that the organization of interdisciplinary working groups during the design and construction phases and the creation, in an early stage, of the actual operation company, Madrid Calle 30, has been one of the key aspects in the success of the objectives fixed.

In the case of safety and ventilation systems, the homogeneity and uniformity goals, could be reached through the preparation of technical specifications which gained the "ideal" criteria to be followed by the engineering companies and technical departments of the construction companies, which were responsible for the elaboration of the detailed projects and the search of imaginative solutions that could appear during the construction phase.

2. VENTILATION CONCEPTUAL DESIGN AND DIMMENSIONING CRITERIA

Strongly related to the construction methods, but focused to the goal of homogeneity in the ventilation conceptual design, the election of the type of ventilation system was conditioned by the main characteristics of the tunnels:

- Geometry: urban topology with high density of surrounding buildings and population highly concerned with environmental impact
- Two different construction methods: TBM section in the By Pass tunnel and Cut and cover in the River Project.



- Traffic composition: prohibition for dangerous goods, low heavy good vehicles (with limitation to the maximum weight up to 8 tonnes and busses)
- Traffic scenarios: fluid flow and possible congestion (even with traffic control measures adopted). AADT up to 100.000 veh /day

- Other operational aspects: High surveillance level, fast response time of (internal and external) fire emergency services, etc.

Based on the characteristics of the project different alternatives were evaluated during the basic design stage. However two main topics were highlighted: environmental impact during normal operation and fire management.

Concerning the environmental management, in shorter tunnels inside the city of Madrid is based on the dispersion of the pollutants through the portals. However, due to the great length of these tunnels the strategy has been double: the definition of shorter ventilation sections and also dilution of the contaminants with large air flow rates.

In this way, a lot of ventilation stations have been installed to split off (in sections of around 600 meters) the contaminant charge to avoid the emissions concentration on a very few points. In addition, reinforcement on the contaminant dilution levels, both inside and outside the tunnels, has been used.

Since there are no specific Spanish guidelines for dimensioning ventilation systems for tunnels (either in normal operation or in case of fire), PIARC reports (PIARC 1995, 1999, 2000, 2004) and French guidelines (CETU, 2005) have been the main references.

According to PIARC criteria, but also considering larger dilution air flows for environmental reasons and since it was expected to have large times of permanence in the tunnels due to congested traffic, a maximum CO level of 30 ppm was considered. Accordingly, parametric studies to calculate the ventilation needs for a standard 3 lanes section, 1 km length tunnel for slopes between -5 and 5%, conduced to air flow rates of 285 m^3/s/km for a 3 lane tunnel.

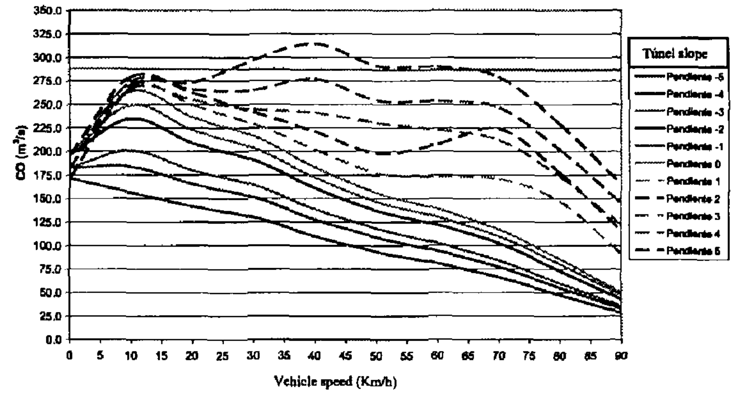


Figure 2: Parametric study for the determination of air flow rates.

In addition to those measures, to improve the quality of the environmental air conditions in the city, particles and NO_2 filtration stations have been installed on the ventilation shafts (4 units of 680 m^3/s each) of the By-Pass Sur (where there was enough space for them), and only particles filtration stations (15 units) on the river section of the project with expected efficiency not below 80% for both PM10 and PM2.5.

These filtration stations have been complemented with electric, control and storage installations and also By-Pass systems to minimize damages in case of fire. It is worthwhile to mention that, as far as four different companies have been contracted to supply the electrostatic precipitators and the filtration stations, it was decided to install, one in each of the ventilation stations, the same model of equipment for the monitoring process of the emission levels and efficiency estimation. It is expected that, in the close future, very useful qualitative and qualitative information about the behaviour of this filtration systems will be available.

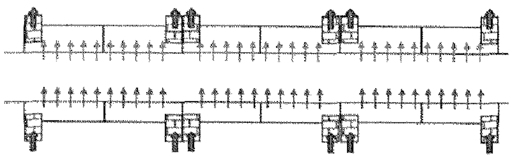
Concerning the fire incident management, taking into account a design fire size of 30 MW, two different approaches were possible, related with the construction method:

- In tunnels where ventilation ducts could be used, mainly the By Pass tunnel constructed with TBM technologies and the links to the adjacent tunnels (A-III link and Section 4), a purely transverse ventilation system was proposed, with a maximum length of 600 meters with separated fresh air and exhaust circuits (Figure 3 a).

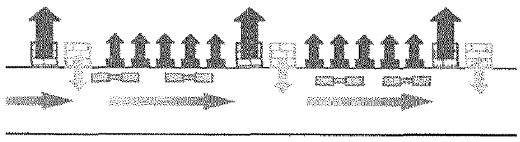
  The fresh air was transported through the duct formed under the carriageway (which should be used also as a evacuation and emergency access way) and supplied to the traffic space through nozzles (70 x 35 cm^2) situated each 10 meters in both sides.

  The exhaust duct, situated above the roof, was designed for the extraction of the vitiated air during normal operation and the smoke in case of fire, which was connected with the traffic space trough, regulated but not remote controlled, openings of 2 m^2 each 25 meters.

  The total air flow capacity is 170 m^3/s per section, i.e. 600 meters, what was accomplished with the construction of ventilation shafts each of one covered not more than 4 ventilation sections and expelled up to 680 m^3/s of treated air.



a) By Pass tunnels



b) River section

Figure 3: General layout of the ventilation system

- In cut and cover tunnels very close to the building and where the existence of other infrastructures (pipelines, underground lines, river channel) made impossible the construction of ventilation ducts a longitudinal system with exhaust reinforcement was proposed.

  The general layout consists on ventilation sections of separated around 600 meters. The air flow enters the tunnel through an injection station and is extracted at the end of the ventilation section. The shafts are complemented by jet fans to direct the air flow movement in the traffic direction (Figure 3 b).

  However, to improve the behaviour of the ventilation system in case of fire it was proposed the installation of additional single exhaust points of 30 m^3/s and separation of 100 – 200 meters, what permitted the desired homogeneity with the transversal solution in case of fire.

  The dimensioning criteria for the exhaust ventilation stations consist is based in the use as massive exhaust points which should allow an air velocity in the way of the traffic higher than the critical velocity. This criteria has been fulfilled with exhaust air flows ranging 200-300 m^3/s what has implied an extraordinary effort to the engineering and construction companies in charge of the detailed engineering design, to achieve innovative solutions and, in case of impossibility, the adoption of complex designs where interconnection dampers or intermediate ducts have been necessary.

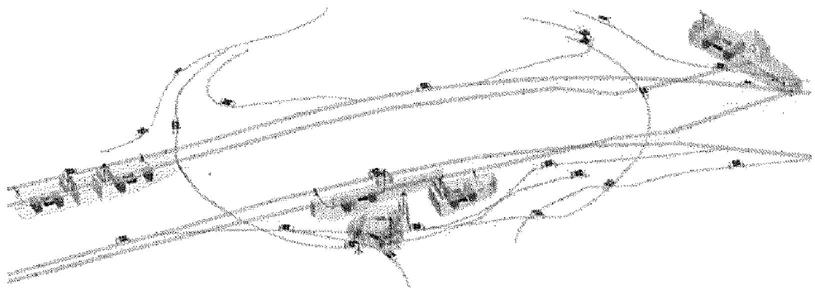


Figure 4: Detailed design for the ventilation system of the River Project

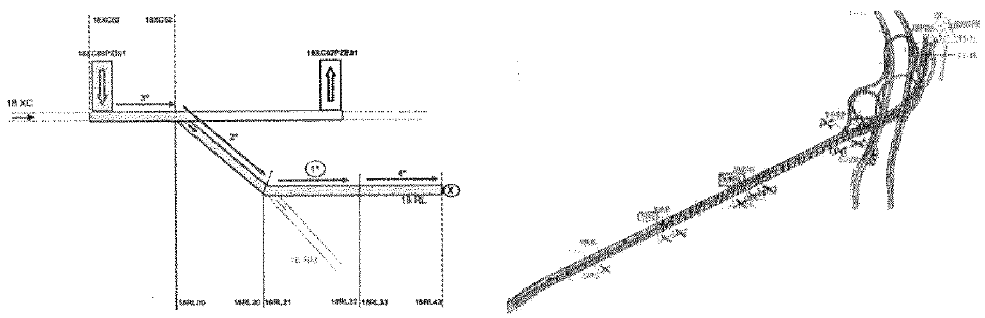
3. VENTILATION CONTROL SYSTEM

Ventilation control system consists of carrying out automatic ventilation operations as well as proposing others actions to the operator in order to facilitate his decision making in any situation. The principal purpose is to minimize the reaction time in either normal or emergency operation.

For **ventilation during normal operation,** a distributed control system has been developed, dividing the tunnels network into sectors which are controlled by independent remote control units. For simplification of the maintenance process, only one algorithm has been developed but specific configuration can be set for each independent ventilation zone.

Control logic is based on regulation by intervals consisting of rules that compare pollutant and velocity (treated) measurements with pre-set reference values. The set values determine the ventilation strategies, and therefore they must be adjusted during normal operation.

Because of the complex road tunnels network, ventilation control during normal operation has been set up in zones called "preferential paths for mechanical ventilation". In order to harmonize ventilation operations, the entire tunnels network has been divided into zones of similar characteristics, in particular, according to the kind of road. The three basic types are: (1) zones which belong to a main road, (2) entries in main roads, and (3) exits from any road.



a) Preferential paths definition for normal operation

a) Predefined automatic actuations in case of fire

Figure 5: Strategies schemes for ventilation control

In case of fire, the ventilation scheme is completely different from normal operation. On one hand, the actions which must be carried out for controlling ventilation in the fire zone depend on the information of other zones. And, on the other hand, synchronized operations must be realized simultaneously over a lot of equipment. Therefore, the ventilation strategies to apply must be based on decisions which are made by the Main Control Centre, including the following stages:

- Detection of fire alarm either automatically by means of linear heat detection system or manually activated by an operator upon visual detection through (CCTV).
- Identification and validation which allows the operator to confirm or not the existing alarm in order to start or avoid the automatic ventilation operations. If there is not any operator response, the control system will confirm automatically the fire after a certain time.
- Ventilation operations: Once the fire location is confirmed, automatic ventilation operations are launched.

From the point of view of the actuations on the ventilation system three stages are defined:

- 'Safety-state': in order to minimize the response time in case of fire, safety ventilation operation starts on as soon as a fire alarm is detected including actuations which are not harmful in case of a false alarm or wrong identification. In general, operations include the stop of ventilation algorithm for normal situation (only in specific zones), the stop of fans which generate high levels of turbulence (supply stations and jet fans) and the starting on of the exhaust system.
- 'Automatic response': after the identification and validation process the following steps will be carried out automatically:
    - operations called 'Initial ventilation' with the main objective of maximize the smoke extraction through both fire-zone and surrounding-zones and, secondly to reduce air velocity in the fire-zone in order to achieve smoke stratification.
    - activation of the algorithm for the longitudinal airflow control to improve the response of the 'Initial Ventilation' if necessary, and, on the other hand, to keep the velocity between reference values, which directly depend on the traffic conditions. For this purpose, the system must to change automatically the reference velocity values as a function of the traffic conditions of previously selected zones.

In addition to those automatic systems other procedures are available to make the necessary changes in ventilation conditions at any time, for example, for supporting Emergency Services.

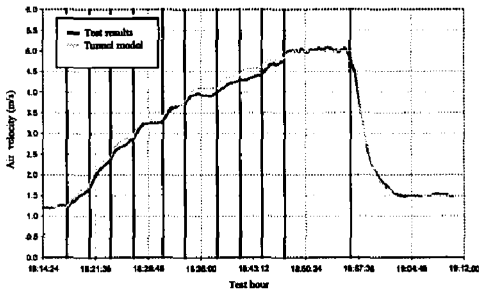
4. IN-SITU VENTILATION TESTS

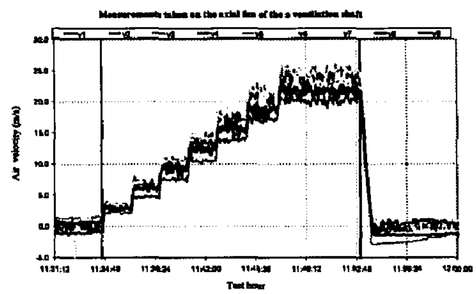
A whole test campaign has been carried out in the Calle 30 tunnels installations by the quality departments in charge of each branch of the project.

Related to the ventilation system, several tests have been carried out in the tunnels: from individual tests of sensors and ventilators to in-situ test to determine parameters of the installation and the verification of the global behaviour of the ventilation system to check how the system behaves when working as a whole (that is to say that every part of the ventilation system and the software programmed for the normal working of the tunnel and in case of fire does indeed work as projected).

Some of these in-situ tests are listed below:

- Verification of the hydraulic behaviour of the ventilation system, jet fans and big axial fans to check their air flow rates, efficiency, rotating speed, electric expense...
- Verification of the hydraulic parameters of the tunnel (friction factor that usually includes wall roughness as well as the lights, information panels,...)





- Verification of the correct working of the fresh and exhaust air ducts and the correct regulation of the dampers regulation (specially in case of fire), on transverse ventilation system.

5. LARGE SCALE FIRE TESTS

In the search of high security levels for the Calle 30 tunnels, the chance of complemented the expected ventilation system with automatic extinction ones was planned.

However, accumulated experience about mixed effects of these two systems is scarce, so it was needed to tackle it from an experimental planning. During 2006, together with Madrid fire department and different manufacturers specialized in water mist systems, a large scale fire tests campaign was carried out.

Among the objectives of these tests it is necessary to emphasize the study of escape conditions in the presence of different ventilation and extinction systems conditions, the verification of control or extinction capability under different ventilation conditions and the firemen participation in extinction tasks and as observers in fire tests for evaluating the systems behavior.

Fire tests were carried out with different predefined loads (normalized wood euro-pallets, diesel pools and real vehicles) with estimated heat released rates between 5 MW and 30 MW (according to the expected fire loads). During the tests, different ventilation conditions (similar to the available ones at the tunnels), temperature evolution, visibility and air velocity were evaluated.

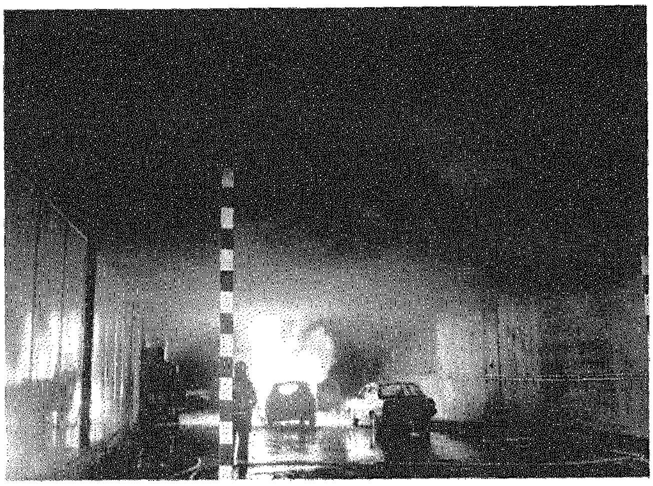
On the other hand, one of the main difficulties for large scale test planning was the need to fix a test matrix that allowed the obtaining of significant results. In this way, among all factors that were involved in an actuation process in case of fire, the decisions taken were based on ventilation and extinction activation times, due to the reaction time depends of non-contemplated factors.

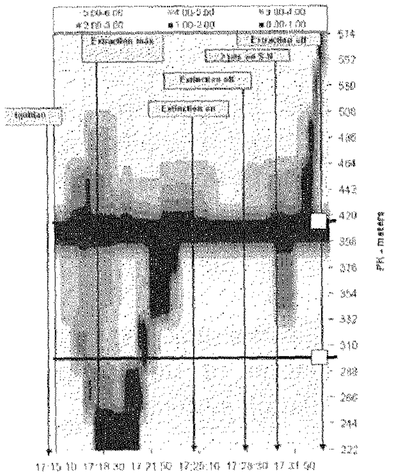
About ventilation system, the test matrix definition was made on two dimensions: passed time up to extraction activation and longitudinal velocity value during the test.

With respect to the extinction system, the considered significant parameters were activation time and fire location capacity of the operator.

Temperature, air velocity and visibility measurements were carried out to evaluate the interaction between ventilation and extinction systems. These tests campaign have provided a lot of valuable data and information to support the decision judgment and to try to avoid interferences between water mist systems and ventilation ones.

In addition, it is necessary to remark, the constant and active Madrid city council fire department participation, not only in the test definition but also in their realization; which has helped them to develop intervention and organization procedures.





6. CONCLUSIONS

The construction of the Calle 30 tunnels represents a very interesting project in which a wide variety of situations had to be covered, in variable traffic conditions. For these reasons, both the project and its development have been a remarkable technical challenge and it has turned into a national and international reference after its completion.

The authors have had the chance to participate on the technical advisement for the definition of the general operation and design criteria of the ventilation system, so that the projects elaborated by the different engineer companies would maintain the necessary homogeneity and coherence. Additionally the authors have participated in the different multidisciplinary workgroups formed during the project development for the management of the environmental issues, fire safety and operation.

The authors warmly appreciate the challenging opportunity provided by Ayuntamiento de Madrid and Madrid Calle 30 to participate in this singular project.

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